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The behaviour of fluid flow in a 90-degree (sliced) nonlinear bend

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Abstract. The behaviour of flow due to nonlinear bends in piping networks involves the occurrence of contractions and turbulence that begin when approaching the upstream part down to the downstream part; these conditions are caused by collisions between fluid particles flowing with pipe walls in sudden direction changes. Though contractions and turbulence occur in all directions along the bends, the normal flow downstream of the bends occurs quite far after the bends. The elements that influence contraction and turbulence are velocities (U), number of slices (n), length of nonlinear walls (L_i), sudden angle changes (α), coefficient of friction (f), acceleration of gravity (g), and the slope of the pipe base (I). A higher flow velocity in a pipe leads to farther laminar flow returns downstream of the bends, and a smaller flow velocity leads to the flow returning to normal downstream shortly after the bends. The simulations of this research involved a 10 m/s initial velocity with a 25.4 mm pipe diameter and the number of slices (n) = 2; normal flow was achieved at 22D after the nonlinear bend. With similar velocity and different diameters of pipes, the length of contraction, turbulence, and laminar flow were equal. This analysis is expected to provide optimal benefits for performance in the usage of nonlinear bends in activities related to piping networks, especially the primary network, which uses large-diameter pipes.

Keywords: nonlinear bend, flow direction change, normal flow, slice numbers (n)

1. Introduction

Pipeline networks are one of the transportation systems that are utilized to serve and send fluids such as fuel in both liquid and gas forms, as well as freshwater. The function of a piping network is optimal if the pipes have been assembled into one system and have formed the network. The formation of these networks is achieved in part through the use of connecting devices, one of which is bends. These connections cause contraction of flow, turbulence of flow, and head loss (h_L).

The theoretical behaviour of flow caused by curve bends and nonlinear bends is generally different, and thus a model needs to be implemented in the field. In their usage, nonlinear bends (slices), especially for pipes of large diameter (steel and HDPE), are easy to make, quick to assemble, and low in cost. Previous studies generally used curve bends. Therefore, this study is a further research on nonlinear bends to obtain an optimal model for the use of nonlinear bends.

The behaviour of flow, as the contraction and turbulence of flow in bends, is caused by the resistance of velocity. This condition occurs because of collisions of water particles with pipe walls and the change of the velocity direction in the pipeline. Previous studies have examined the head loss that occurs in a 90° bend [1, 2], flow behaviour in a 90° bend with a large curvature ratio using numerical investigations



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[3], flow characteristics due to bends in the velocity field [4, 5], and efficiency and optimization of flow through bend pipes [6].

Other studies include research and investigation on the analysis and study of turbulent flow in pipe bends [7], the effect of bend radius on erosion that occurs in S-shaped pipe bend wall [8], and the flow changes and velocity distribution that occur due to the influence of guides in a 90° bend pipe [9].

The developed model in this research is the factors that affect the flow in the bend. The nonlinear bend model has various slices, which has to be considered in relation to the effectiveness and efficiency of application on the field. Looking at previous references, the results of the analyses show non-uniformity. Past literature and research only cover two types of curves. In identifying previous studies, research results on bends vary, and almost all studies focused on curvilinear curves. Thus, this subject needs further analysis in order to obtain an optimal model.

2. Materials and Methods

2.1. The Geometry of 90-Degree Nonlinear Bends

The utilized analysis in this research was based on conditions in the field that often occur in Indonesia, which is that usually, plans for curve bends run into obstacles when constrained by the needed material, specifically for pipes of large diameter (steel and HDPE). Based on the background and field conditions that are often encountered, they have illustrated the need to conduct scientific studies so that the phenomenon in the field can be examined and can be used as a scientific basis. This matter is closely related to the implementation in the field, and thus can be analysed proportionally.

The head loss and flow turbulence in a nonlinear bend are due to the friction of the wall (L_i) and are influenced by sudden angle changes (α), which slows down the flow. The influencing elements are velocity (U), number of slices (n), the average length of nonlinear walls (L_i), angle changes (α), friction coefficients (f), gravitational acceleration (g), and additionally pipe slope (I). According to the prior described hypothesis, the analysis concept of nonlinear bends is explained in Figure 1 below:

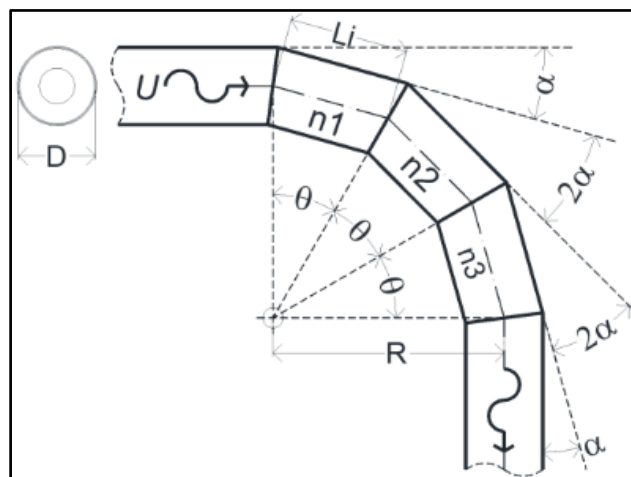


Figure 1. Model of a pipe with a 90° nonlinear bend

In order to explain the pressurized pipeline, D (diameter), U (velocity), and the scheme of the model as in Figure 1 above is used. The bend uses a nonlinear model consisting of the number of slices (n), the radius (R), length of the wall (L_i), and the change in the direction of flow ($n+1$). The angle is divided by the number of slices (n); the first and last angles of change are α and the angles formed between the upstream and downstream sections is 2α up to $n-1$. The primary force of head loss in nonlinear bends is friction, which occurs between the fluid and the wall of the pipe slices, and due to sudden direction changes.

2.2. Analytical Considerations

The concept was developed based on the scheme as in Figure 1; the decrease in the equation is described by calculating the head loss coefficient. Figure 1 explains a kind of slice model with 3 slices. Each section of the slices is an equal segment, but the bend angles are different. The angles after the first and before the last bend are α , but the angles between the first and last bends are always 2α . The angle changes suddenly cause the flow to slow down; with the analytical vector approach, angular changes are the function of directional changes. The initial equation is the cosine of the difference of a single bend, and ultimately can be explained as the following:

- ✓ the angles of change formed by the nonlinear bend on the first and last angle direction change are equal to α ;
- ✓ the angles of change after the first and before the last formed angle direction change are equal to 2α ;
- ✓ the number of slices (n) is 3; with angles α (2 points) and angles 2α (2 points), the value of the vectors is

$$\cos^2 \alpha \cdot \cos^{(n-1)} 2\alpha \quad (1)$$

- ✓ the number of slices is (n) = 1; with $\cos^{(n-1)} 2\alpha = \cos^{(0)} 2\alpha = 1$, Equation (1) is $\cos^2 \alpha \cos^{(0)} 2\alpha = \cos^2 \alpha$.

3. Results and Discussion

3.1. Friction

According to the Darcy Weisbach equation, the head loss due to friction in a nonlinear bend is the friction of the wall at every slice of the bend (nLi). With the hL coefficient due to friction being (δ_a), the equation becomes

$$Li = \frac{Y}{\cos \alpha} = \frac{R \sin \theta}{\cos \alpha} \text{ substitution to 2; } \delta_a = f \frac{L}{D}, \text{ thus, the equation is}$$

$$\delta_a = f \frac{L}{D} = f \frac{Li}{D} = f \frac{R \sin \theta}{D \cos \alpha} \quad (2)$$

If the number of slices is more than 1 or $n > 1$, the equation is

$$\delta_a = f \frac{n \cdot R \sin \theta}{D \cos \alpha} \quad (3)$$

The coefficient of friction (f) as in Equation 3 and the value of the Reynolds number (Re) are used to obtain the value of the coefficient friction. Then, the value of friction coefficient (f) is indicated in Table 1 below [10]:

Table 1. The friction coefficient for smooth pipes with friction equations

Equation	Friction coefficient (f) formulas	(Re) range	Notes
Darcy Weisbach	$f = 64 Re^{-1}$	$< 3 \times 10^3$	Laminar
Blasius	$f = 0,3164 Re^{-1/4}$	$3 \times 10^3 \sim 1 \times 10^5$	Turbulent
Nikuradse	$f = 0,0032 + 0,221 Re^{-0,237}$	$1 \times 10^5 \sim 3 \times 10^6$	Turbulent
Karman-Nikuradse	$f = 1 / [2 \log_{10} (Re \sqrt{f}) - 0,8]^2$	$3 \times 10^3 \sim 3 \times 10^6$	Turbulent
Itaya	$f = 0,314 / [0,7 - 1,65 \log_{10} (Re) + (\log_{10} Re)^2]$	-	Turbulent

Source: Nakayama, Y. and Boucher, R. F., (1998), p115-116

3.2. Head loss by change in the direction of flow

The head loss caused by the change in the direction of the flow is an accumulation of sudden angle changes. To find out of the total coefficient of head loss due to changes in the direction of flow, Equation (4) can be used. The initial flow upstream of the bend is still 100%, and downstream of the bend, the flow is no longer 100%. Furthermore, the coefficient of direction change of flow is denoted as δ_b , and then the equation is:

$$\delta_b = 1 - [Cos^2 \alpha . Cos^{(n-1)} 2\alpha] \quad (4)$$

For an upstream flow value (100%), due to the accumulation of sudden angle change in a nonlinear bend, the coefficient is Equation (4). The combination of friction coefficients and the coefficient of direction change of the flow is the total head loss in a nonlinear bend. If K_b is the total loss coefficient in nonlinear bend, the final equations are Equation (3) + Equation (4), and the value of K_b is

$$K_b = \delta_a + \delta_b = f \frac{n \cdot R \sin \theta}{D \cos \alpha} + 1 - [Cos^2 \alpha . Cos^{(n-1)} 2\alpha] \quad (5)$$

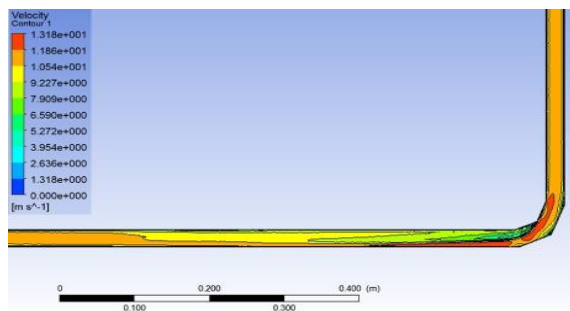
Thus, the head loss of the nonlinear bend becomes

$$hL = K_b \frac{U^2}{2g} = \left[f \frac{n \cdot R \sin \theta}{D \cos \alpha} + 1 - [Cos^2 \alpha . Cos^{(n-1)} 2\alpha] \right] \frac{U^2}{2g} \quad (6)$$

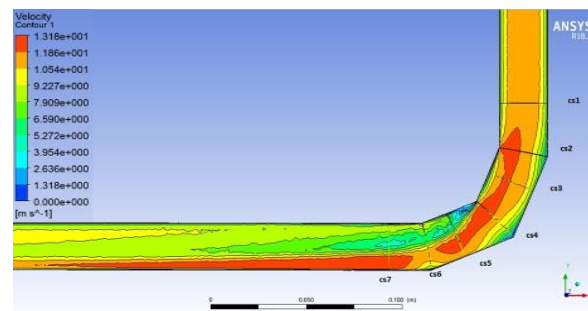
3.3. Behaviour of flow

Philosophically, the fluid flowing in the pipeline becomes contracted when the pipe leads to a constriction or enlargement, changing the direction of flow. The contraction causes collisions between water particles, causing turbulence in the flow of the pipe. The discussion of this research focuses on the direction change of flow and the friction of the wall in a nonlinear bend as the bend type being examined.

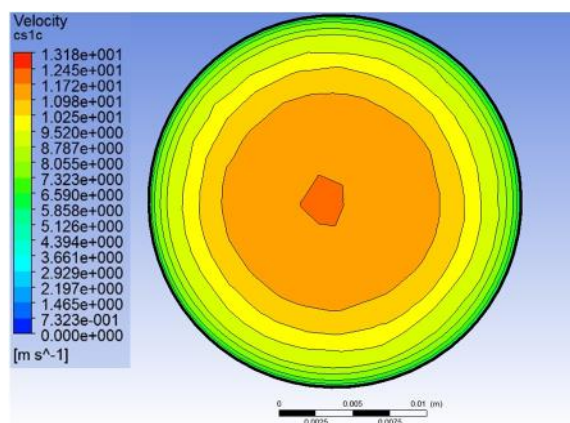
With the nonlinear bend model, the behaviour of contraction from the water flow causes turbulence up to the downstream part of the pipe. The length of turbulence in the downstream part of the bend is shown in Figure 2. In addition to turbulence of flow, the downstream part of the bend creates a pressure drop or head loss.



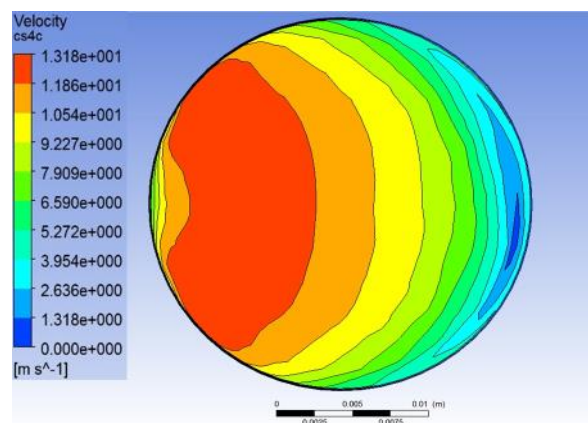
(a) Velocity Contour of U



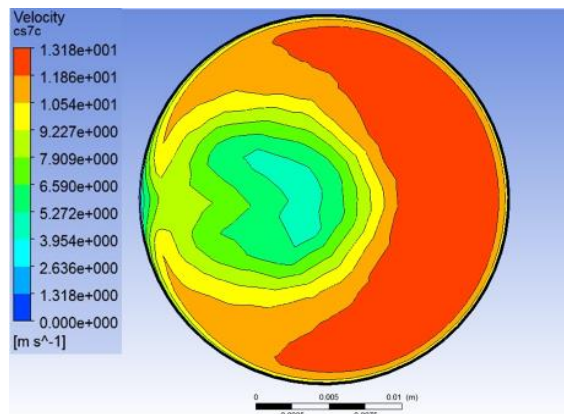
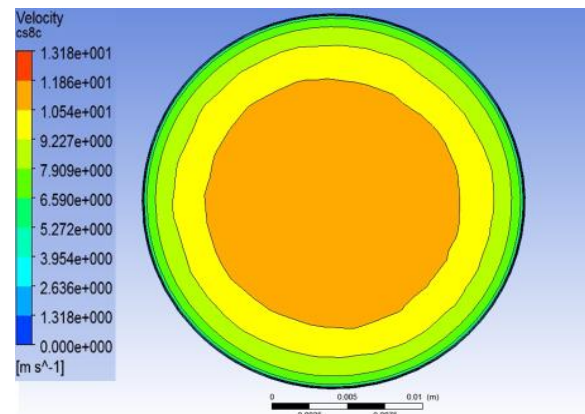
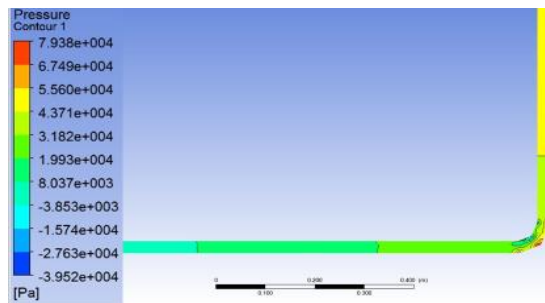
(b) Section arrangement of U



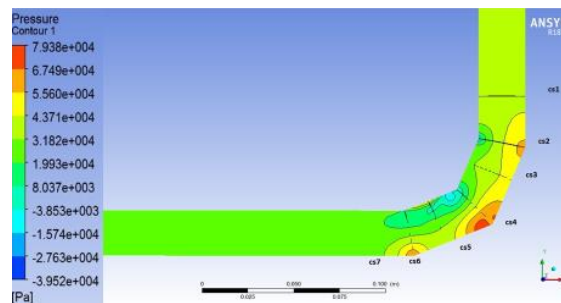
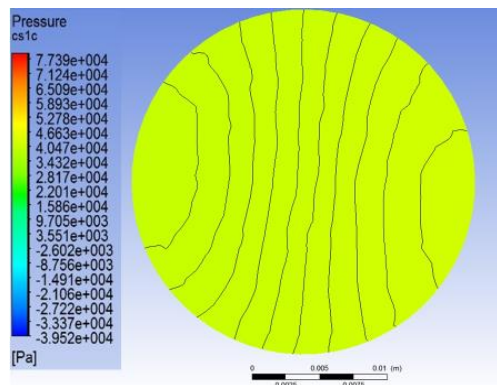
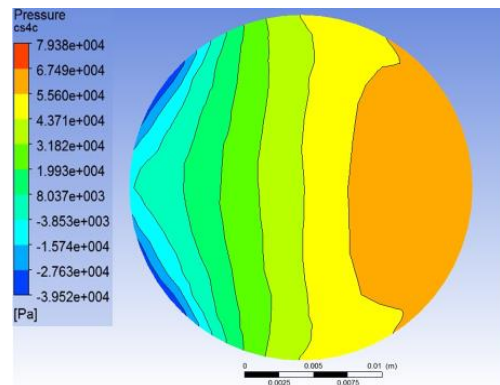
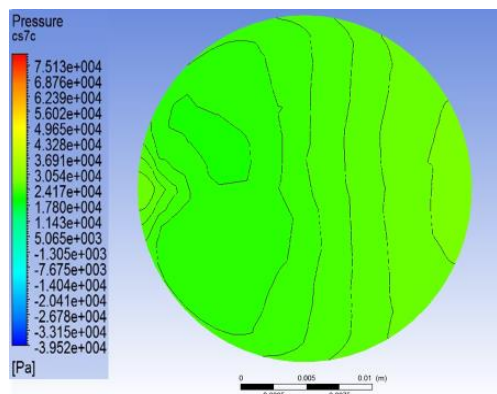
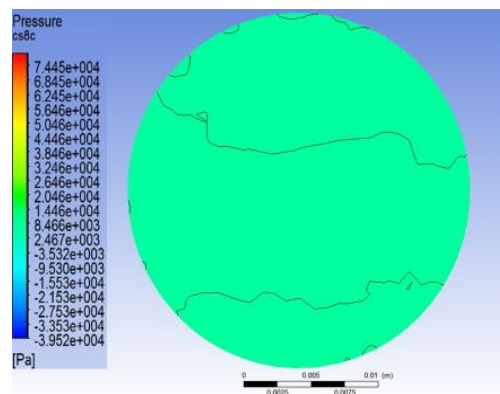
(c) The upstream section of U



(d) The midsection of U

(e) The downstream section of U (f) After 22D, downstream of U 

(g) Head loss contour

(h) Section arrangement of hL (i) The upstream section of hL (j) The midsection of hL (k) The downstream section of hL (l) After 22D downstream of hL **Figure 2.** The behaviour of flow and head loss of a nonlinear bend

The simulations of flow in this study utilized a 10 m/s initial velocity with a 25.4 mm pipe diameter and the number of slices (n) = 2; normal flow occurred at 22D after the nonlinear bend. The pressure that occurred in the simulation was 4.371×10^4 Pa upstream of the bend and became 3.182×10^4 Pa downstream of bend. Thus, the head loss in the nonlinear bend with the number of slices (n) = 2 is equal to 1.189×10^4 Pa.

Table 2. Head loss of a 90-degree nonlinear bend

Item	Unit	90° Nonlinear bend, D = 5/8"				
Pipe diameter (D)	(inch)	5/8"	3/4"	1"	5/4"	6/4"
Discharge (Q)	liters/minute	30	30	30	30	30
Friction (δ_a)	-	0.01240	0.01298	0.01395	0.01475	0.01543
Direction change (δ_b)	-	0.30007	0.30007	0.30007	0.30007	0.30007
Coef. of hL (Kb)	($\delta_a + \delta_b$)	0.31247	0.31305	0.31402	0.31482	0.31550
Head Loss (hL)	(cm)	10.17314	4.915135	1.559998	0.640603	0.3096

Source: *Analysis Results*

According to the calculation method, the discharge (Q) is 0.60 to 39.00 litres/minute; the graph of the relationship between discharge and head loss in a 90° nonlinear bend with $n = 3$ is shown in Figure 4.

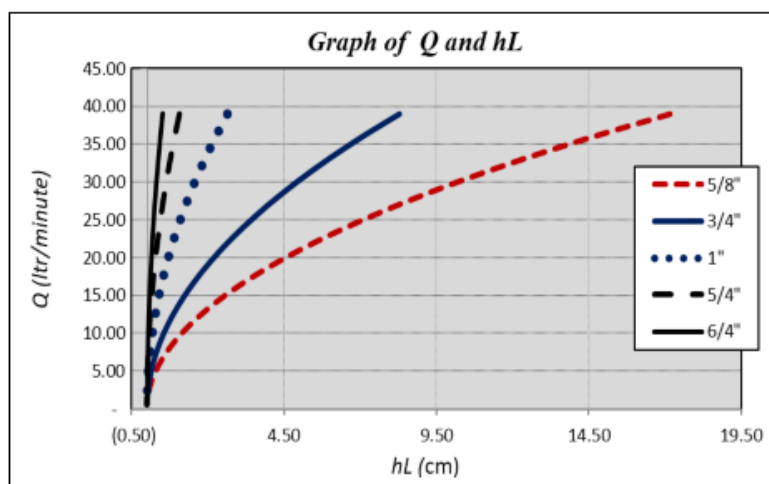


Figure 3. Graph of discharge (Q) and hL

Table 3. Head loss coefficient of a 90-degree nonlinear bend with a variety of slices

Item	Unit	90° Nonlinear bend, D = 5/8"						
Discharge (Q)	(liters/minute)	30	30	30	30	30	30	30
Number of slices (n)	pieces	1	2	3	4	5	6	7
Friction (δ_a)	-	0.01543	0.01278	0.01240	0.01227	0.01222	0.01219	0.01217
Direction change (δ_b)	-	0.50000	0.39644	0.30007	0.24139	0.20187	0.17347	0.15207
Coef. of hL (Kb)	($\delta_a + \delta_b$)	0.51543	0.40922	0.31247	0.25366	0.21409	0.18566	0.16424
Number of slices (n)	pieces	8	9	10	11	12	13	14
Friction (δ_a)	-	0.01215	0.01215	0.01214	0.01214	0.01213	0.01213	0.01213
Direction change (δ_b)	-	0.13538	0.12199	0.11101	0.10184	0.09407	0.08741	0.08162
Coef. of hL (Kb)	($\delta_a + \delta_b$)	0.14753	0.13414	0.12315	0.11398	0.1062	0.09954	0.09375
Number of slices (n)	pieces	15	16	17	18	19	20	21
Friction (δ_a)	-	0.01213	0.01212	0.01212	0.01212	0.01212	0.01211	
Direction change (δ_b)	-	0.07208	0.0681	0.06454	0.06133	0.05843	0.055965	
Coef. of hL (Kb)	($\delta_a + \delta_b$)	0.08421	0.08022	0.07666	0.07345	0.07055	0.068075	

Source: *Analysis Results*

The pressurized pipes have $D = 5/8" = 1.59$ cm and $R = 3.18$ cm. The discharge (Q) is 0.50 litres/s = 500 cm³/s = 30 litres/minute. The pipe cross-sectional area (A) is 1.98 cm², and the velocity (U) is 252.74 cm/s. Testing was carried out with friction coefficient (f) = 0.00386 and the Reynolds number (Re) = $45.081 \times 10^6 > 4000$, using numbers of slices (n) from 1 to 20 pieces and the angles θ and α depending on n ; according to Equation (5), the full values of δ_a and δ_b and then K_b are obtained as in Table 3 below.

Based on Table 3, the head loss coefficient and the number of slices were implemented, as shown in Figure 5.

Figure 4 explains the results of simulation equations for a nonlinear bend with various numbers of slices. Each gives a different head loss coefficient. The graph also explains that the trend obtained from the simple simulation is according to the hypothesis: for a nonlinear bend with a greater number of slices, the shape of the bend becomes more excellently or perfectly curved. Similarly, for the head loss coefficient, with more slices, the head loss coefficient becomes smaller.

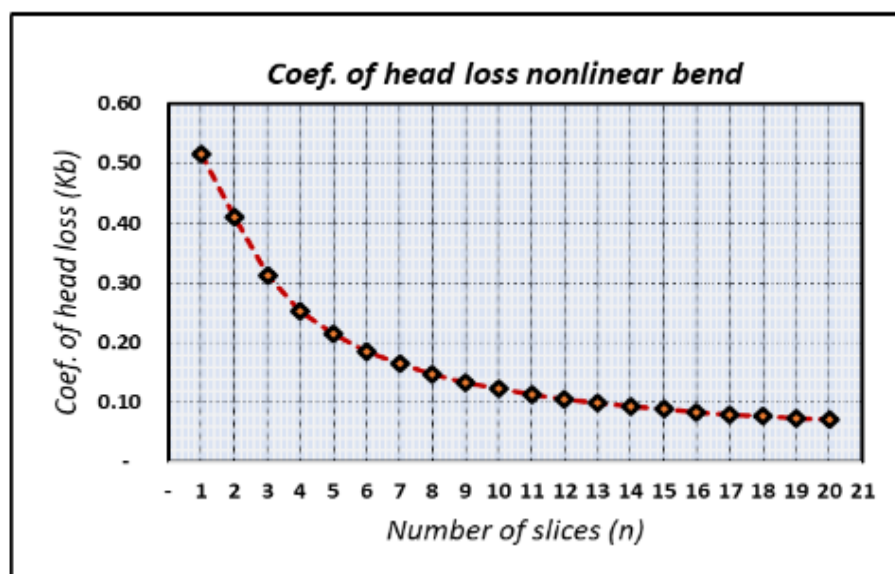


Figure 4. The value of K_b and n of a 90° nonlinear bend

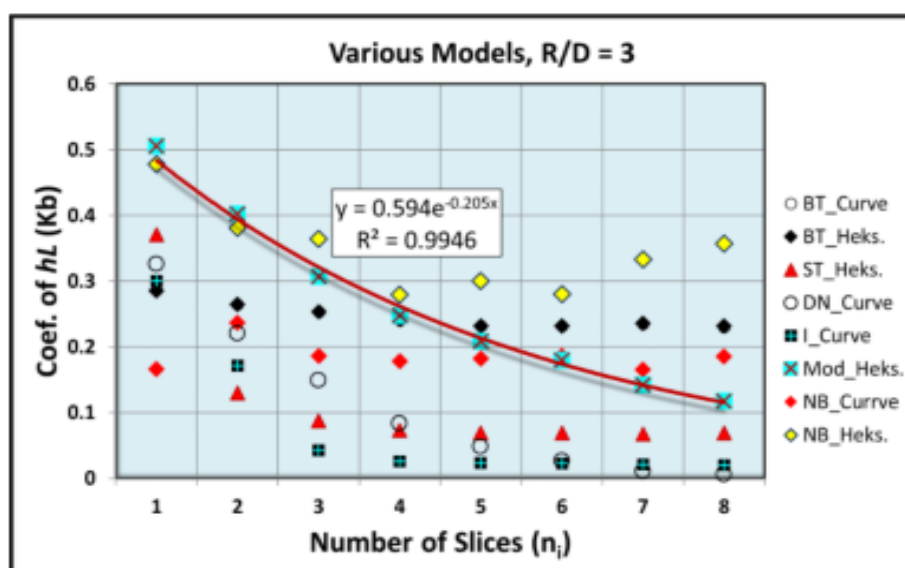


Figure 5. The value of K_b with various models

Figure 5 explains the simulation of nonlinear bend models with various models. Overall, the nonlinear bend model explains that with more slices, the coefficient of hL is smaller, and with fewer slices, the coefficient of hL is larger. Figure 5 in brief shows that the research hypothesis is accepted.

4. Conclusion

The value of the head loss for a 90° nonlinear bend depends on friction and the change in the direction of the flow, and thus the head loss (hL) is equal to Equation (6). By Equation (6) above, for a fixed discharge through a nonlinear bend, the behaviour of flow and head loss are influenced by the diameter of the pipe and the model of the nonlinear bend. The nonlinear bend model depends on the number of slices (n) and the radius of the bend.

The contraction causes flow turbulence through the nonlinear bend. Turbulence due to the nonlinear bend occurs for a long time in the downstream part of the bend. According to the hypothesis, it is concluded that the trends obtained from these equations showed relevant and identical results for application to pipe networks.

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